

DIVISION S-10—WETLAND SOILS

Modeling of Carbon Sequestration in Coastal Marsh Soils

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ABSTRACT

Two transects were established across submerging coastal landscapes in Dorchester County, Maryland. Extensive sampling protocol was performed along the submerging upland tidal marsh soils to model C sequestration. Coastal marsh soils are accreting vertically and migrating laterally over the low-lying forest soils to keep pace with sea-level rise. The predictive C sequestration model was a two-step linear function. Therefore, C sequestration will continue to occur by accumulation in the organic horizons and sea-level rise is the driving force. During the last 150 yr, the rate of C sequestration averaged $83.5 \pm 23 \text{ g m}^{-2} \text{ yr}^{-1}$. Before the last few hundred years, the predicted long-term rate of C sequestration averaged $29.2 \pm 5.35 \text{ g m}^{-2} \text{ yr}^{-1}$. Sampling protocol and model validation ascertain the validity of the model and placed 80% confidence and 10% accuracy on rates of C sequestration and the predictive model. The model indicated that coastal marsh soils have higher C storage capacity than upland forest soils, and soils in the Cumulic subgroup of Mollisols. In general, C storage in mineral soils tends to reach a steady-state condition, whereas C sequestration in coastal marsh soils is a continuous phenomenon. During the next century, future C sequestration in the newly formed coastal marsh soils averaged $400 \pm 162 \text{ g m}^{-2} \text{ yr}^{-1}$. Modeling C sequestration in coastal marsh ecosystems indicated that C storage under positive accretionary balance acts as a negative feedback mechanism to global warming.

IN COASTAL SUBMERGING ENVIRONMENTS, the frequency of tidal inundation with brackish water increases with decreasing elevation of the landscape toward the marsh/terrestrial edge (Hussein and Rabenhorst, 2001). This tidally influenced environment increases the effect of salinization process with decreasing elevation and creates a dynamic ecological gradient as well as the subsequent changes in the biological community structure. As sea-level rise continues, the frequency of tidal inundation increases progressively with time creating a soil environment that encourages salt-tolerant plants to colonize the low-lying once agricultural and forest soils. Upon permanent submergence, the high osmotic potential of the soil environment kills forest species and eventually salt-tolerant plants become the dominant vegetative cover (Brinson et al., 1985; Gardener et al., 1992). These marsh plants tend to entrap tidal sediments, add organic matter to the geomorphic surfaces, and prevent erosion. The addition of organic matter and sediment

entrapment allows for the vertical accretion and the lateral expansion of coastal marshes along the landscape. As time progresses, the newly formed submerged upland tidal marsh soils become characterized by thickened organic horizons overlying what once was upland soils.

Carbon is sequestered when atmospheric CO_2 is captured by plants during photosynthesis and stored as organic compounds in the biomass and soils. The surface and subsurface biomass production (primary production) in coastal marsh ecosystems is a major contributor to C pools. The primary production of coastal marshes varies with latitude (Turner, 1976), nutrient availability (Patrick and Delaune, 1972), marsh environment, and chemical properties (Morris et al., 1990). Nevertheless, the net primary production of tidal marshes is generally high, especially in the southern coastal plain of North America where it averages $8000 \text{ g m}^{-2} \text{ yr}^{-1}$ (Mitsch and Gosselink, 1993).

Physical factors such as marsh-surface elevation and tidal range tend to control the frequency, and duration of inundation, as well as depth of flooding in coastal marsh ecosystems (Cahoon and Reed, 1995). The integrated effect of these controlling factors is manifested in the ecological zonation within tidal marsh ecosystems (Redfield, 1972). The ecological gradient within marsh ecosystems and the ability of marsh plants to compete determines the spatial distribution of marsh vegetation (Osgood and Zieman, 1993), and thus the overall marsh-primary production. Along the eastern shore of Chesapeake Bay, low marshes are dominated by Salt-marsh cordgrass (*Spartina Alterniflora*), whereas high marshes are often a complex mosaic of different plant species (Tiner and Burke, 1995).

Mineral sediments brought by tidal water provide nutrients for marsh plants. This may be a limiting factor that determines the overall marsh-primary production. Sediment input is greatly controlled by sediment source, tide amplitude, frequency and duration of tide, mean annual temperature, and the symmetry of tides (Steven-son et al., 1985, 1988). Distribution of sediment input within marsh ecosystems is controlled by proximity to tidal creeks where sediment input near streamside marshes is much higher than that of inland marshes (Leonard et al., 1995).

The dominant peraquatic moisture regime in coastal marsh ecosystems promotes the sequestration of atmospheric C, and the concomitant vertical accretion. Coastal marsh ecosystems are generally oxygen-depleted in which anaerobic decomposers prevail. Therefore, the efficiency of organic matter decomposition in coastal marsh eco-

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Abbreviations: MHW, mean high water.

systems is lower than in soils under aerobic environment (Humphrey and Pluth, 1996; Amador and Jones, 1997).

In coastal marsh ecosystems, stored C is exported to the atmosphere and to adjacent estuaries. The annual CO₂ flux from brackish marshes in the Barataria Basin of Louisiana was estimated to be 180 g C m⁻² (Smith et al., 1983). Waterborne C (inorganic, dissolved organic, and organic particulate) may leave coastal marsh ecosystems through a tidal ebb however, the significance of C export remains in question. Carbon export from coastal marshes to adjacent estuaries ranges from 100 to 200 g m⁻² yr⁻¹ (Nixon, 1980). Due to poor tidal exchange, exported C particulate from Maryland coastal marshes was as low as 7.3 g m⁻² yr⁻¹ (Heinle and Flemer, 1976). Nevertheless, during storm events, a large amount of organic materials suspended by wave actions during high tides may be flushed out of coastal marshes (Stevenson et al., 1988).

The balance between addition, and removal of C determines whether there is C sequestration or loss occurring in the submerged upland tidal marsh ecosystems. The objectives of this study were (i) to develop a predictive model for C sequestration in the submerged upland tidal marsh soils of the Chesapeake Bay, Maryland; (ii) to estimate present and future rates of C sequestration; and (iii) to compare C sequestration in coastal marshes versus mineral soils in agro-ecosystems and upland forest-ecosystems.

MATERIALS AND METHODS

Field Procedures

A marsh reconnaissance survey was performed in Dorchester County, Maryland to select two sites in geomorphic settings where coastal marshes were not subject to direct wave action and showed minimum anthropogenic disturbance. Hell Hook (38°21' N lat., 76°10' W long.) and Cedar Creek (38°19' N lat., 76°4' W long.) marshes were selected to represent the submerged upland tidal marsh soils in the area. At each site, a transect was established along the low-lying uplands extending across tidal marsh soils to the marsh edge by the main stream that feeds the marsh. A detailed topographic survey was performed using a level and was surveyed back to a reference point of known elevation. Elevation of the soil surface was measured every 10 m. Thickness of the organic horizons overlying the submerged mineral soil was also measured every 10 m using a McCauley auger. To develop the predictive C sequestration model, nine marsh pedons (sampling units) (1–2 m²) were selected along each transect to represent the range in marsh ecology and habitats. For model validation, an additional four sampling units were selected along each transect. Within each sampling unit three marsh cores were collected to estimate C storage. This sampling protocol assured 10% accuracy (allowable percentage of deviation from the estimated mean value) and permitted 80% probability statement for the C sequestration model (Hussein and Rabenhorst, 1999a). The upper 125 cm of the organic horizons was collected using 7.5-cm diam. Al tubes, 1.5 m in length. Compaction during sampling was assessed by comparing depth of sampling to thickness of the cores and only those cores that showed ≤5% compaction were actually collected. Upon sample collection, tubes were filled with marsh water, and sealed to minimize oxidation during transport. Organic samples deeper than

125 cm were collected using a McCauley auger to minimize compaction. Peat samples were sectioned into 25-cm increments (unless soil morphology suggested otherwise), placed into plastic bags, sparged with N gas, and frozen in dry ice. The *n*-value of the underlying estuarine sediments at Hell Hook site was determined in the field by squeezing a sample in the hand (Soil Survey Staff, 1998a). In the laboratory, all samples were stored at -15°C. until they were analyzed. To determine long-term rates of marsh vertical accretion, five basal peat samples were collected from each marsh for ¹⁴C dating. To minimize the impact of autocompaction on the estimated rates, peat samples were collected immediately above the dense submerged mineral soils using a McCauley auger. For ²¹⁰Pb dating, three 50-cm cores were collected from each marsh using a McCauley sampler. To account for marsh spatial variability, these cores were collected to represent different marsh environment and vegetative cover.

Laboratory Procedures

Frozen cores were allowed to thaw under N gas and sectioned into 25-cm increments unless soil morphology suggested otherwise. During this process, the recorded magnitude of compaction (≤5%) was distributed linearly along the core's length. The degree of organic matter decomposition was determined by rubbing the organic material with fingers and estimating fiber content (Soil Survey Staff, 1998a). The mineral component incorporated within the organic horizon was assessed as fiber content was estimated. The total weight of the three peat samples collected at a particular depth increment was recorded to determine bulk density. The samples were then composited in preparation for analysis. The gravimetric moisture content was determined using a subsample of at least 0.5 kg of wet peat, and was oven dried at 60°C (approximately 48 h). Using a stainless steel plant mill, the peat subsamples were ground and then ground again using pestle and mortar, to pass a 0.25-mm sieve. Organic C was determined by high temperature combustion using a Leco 60 CNH analyzer with IR detectors (Leco Corp., Joseph, MI). The marsh accretion rates for the last 150 yr were determined using ²¹⁰Pb following standard methods (Flynn, 1968; Benoit and Hemond, 1988). The cores were sectioned at 3-cm intervals and each increment was weighted to determine bulk density and moisture content. Samples were oven dried at 60°C and ground to pass 0.25-mm sieve in preparation for ²¹⁰Pb analysis. Assuming secular equilibrium between ²¹⁰Pb and its granddaughter ²¹⁰Po, the total ²¹⁰Pb activity was determined by counting the α-decay rate of ²¹⁰Po. The depth distribution of the total ²¹⁰Pb activity was used to determine the unsupported ²¹⁰Pb activity. The logarithmic plot of the unsupported ²¹⁰Pb versus depth was used to estimate the marsh vertical accretion rate in the Chesapeake Bay area during the last 150 yr. Carbon-14 dating of the five basal peat samples collected from each site were used to quantify the age-elevation relationship and estimate the long-term marsh vertical accretion rate for the last one or two millennia. The ¹⁴C analyses were performed by Beta Analytic Inc. (Miami, FL).

RESULTS AND DISCUSSION

Site and Soil Characteristics

The upland portions of Hell Hook and Cedar Creek sites are characterized by very gentle slopes and both marshes showed no field indicators of marsh erosion, losses, or major hydraulic alteration. Marsh surfaces are generally characterized by microscale undulating

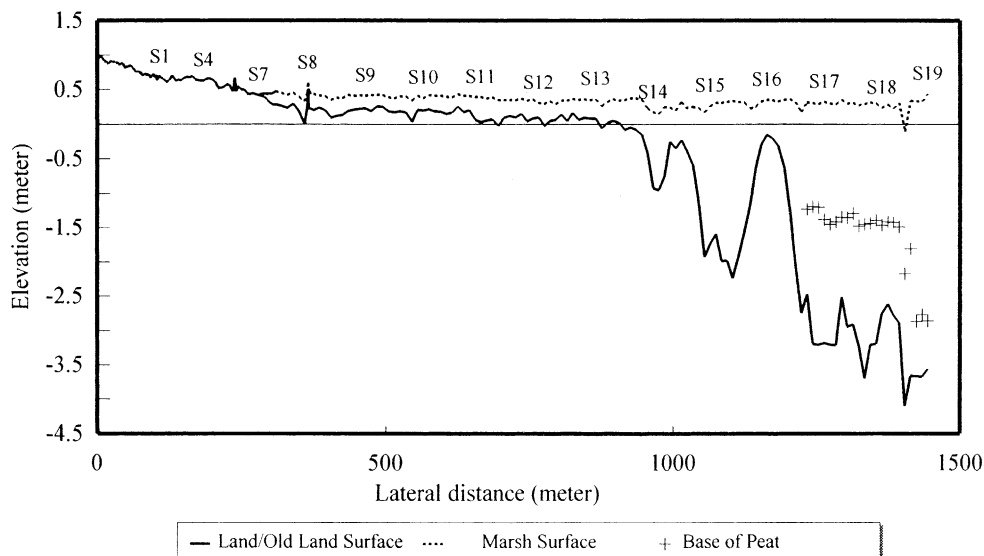


Fig. 1. Topographic cross-section of Hell Hook marsh showing the present marsh surface and the surface of the submerged mineral soil. Beyond Site 17 (S17) to Site 19 (S19), the organic horizons are underlain by estuarine sediments.

topography (Fig. 1, 2). The microtopography is generally attributed to variation in plant species, and vegetation density causing uneven distribution of organic matter accumulation and sediment entrapment within marsh ecosystems. Faunal pedoturbation may also contribute to the undulating topography of marsh surfaces. The Hell Hook marsh occupies an area of about 2.5 km², whereas the Cedar Creek marsh occupies an area of about 3.2 km².

Adjacent uplands to both marshes (Site 1 [S1]–Site 10 [S10] at Cedar Creek and S1–S6 at Hell Hook), were dominated by Loblolly pines (*Pinus taeda* L.) (Fig. 1, 2). At Cedar Creek marsh, the vegetative cover in the transitional zone (S9–S10) was a mixture of Loblolly pine and Salt-meadow cordgrass [*Spartina patens* (Aliton) H. L. Muhl.] as understory. The Loblolly pine showed signs of osmotic stress including dead trees toward the marsh/terrestrial edge. At Hell Hook, the vegetative cover in the transitional zone (S6–S7) was a mixture of shrubs and Salt-meadow cordgrass as ground cover. The vegetative cover along the marsh portions of both transects (S7 and beyond at Hell Hook and S10 and beyond at

Cedar Creek) was a complex mosaic of different plant species, which included Salt-meadow cord grass, narrow-leaf cattail (*Typha angustifolia* L.), common three-square (*Scirpus americanus pers.*), salt grass [*Distichlis spicata* (L.) Greene], and needle rush (*Juncus roemerianus* Scheele).

Upland soils of both sites were within the central concept of Mattapex (fine-silty, mixed, active, mesic Aquic Hapludults) or Elkton (fine-silty, mixed, active, mesic Typic Endoaquults). Soils of the transitional zones were mapped as consociation of Sunken series (fine-silty, mixed, active mesic Typic Endoaquults) (Brewer et al., 1998). While soils of the transitional zones were progressively inundated with brackish water with decreasing elevation, they maintained the acidic nature of Ultisols (Hussein and Rabenhorst, 2001). These soils have not transformed to Alfisols due to high pH dependent acidity and increasing selectivity of the colloidal complex for Al with increasing ionic strength (Hussein and Rabenhorst, 2001). Soils of the marsh zones along both transects were mapped as consociation of Honga series (loamy, mixed, euic, mesic Terric Sulphemists). Soils with or-

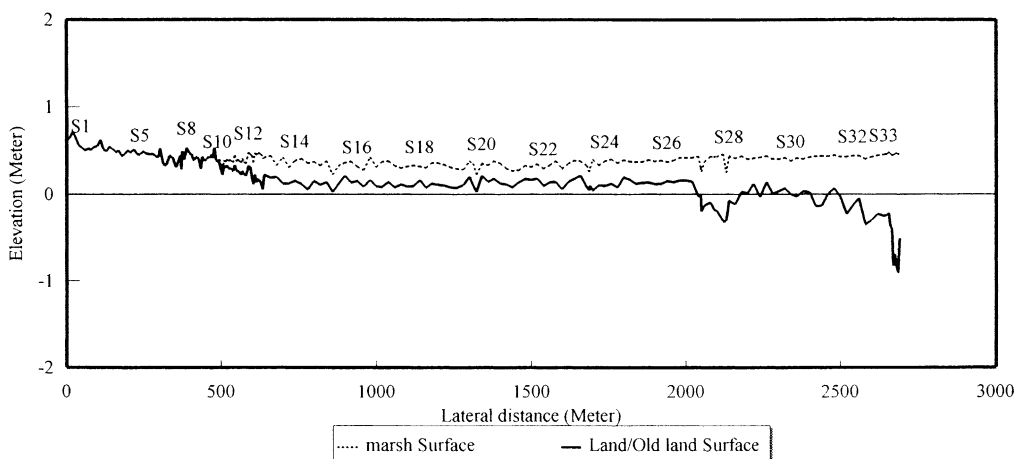


Fig. 2. Topographic cross-section of Cedar Creek marsh showing the present marsh surface and the surface of the submerged mineral soil.

ganic horizons that are <40 cm within the upper 80 cm of the soil profile are not considered Histosols (Soil Survey Staff, 1998a). Therefore, most soils of Cedar Creek marsh (S11–S25) are dissimilar and should not be included in the map unit. At Hell Hook marsh, approximately half of the soils (S7–S13) were not Histosols and the remaining soils were Typic Sulphemists.

Organic horizons at Cedar Creek marsh were underlain by dense, low n -value (high bearing capacity) submerged mineral soils (Fig. 2). At Hell Hook marsh, organic horizons (S7–S17) were also underlain by submerged mineral soils whereas beyond S17 to S19 the organic horizons were underlain by high n -value estuarine sediments ($n > 1$ as estimated in the field) (Fig. 1). Organic horizons of both marshes had no recognizable mineral-sediment layers suggesting that major storm events had no unusual effects on marsh development. Laboratory observations indicated limited to negligible mineral sediments incorporated within the organic horizons. Generally the estimated mean high water for the vicinity is 0.3 m (Hussein and Rabenhorst, 2001) indicating low tidal energy and low sediment input (Stevenson et al., 1985, 1988). However the physiographic positions of both marshes reflect differences in tidal regimes and thus sediment loads (Hussein and Rabenhorst, 2001). The low bulk density of the organic horizons (Table 1), field and laboratory observations supported the low mineral-sediment input as inferred from tidal dynamics. Therefore, both marshes are predominantly accreting vertically by organic C sequestration. The upper 25 cm of the organic horizons was generally fibric in nature, whereas the subsurface and bottom tiers were generally hemic in nature (Table 1). Generally, the depth distribution of C in Histosols underlain by mineral soils showed a zone of maximum C sequestration, and a gradual decrease in organic C to reach a minimum value at the organic-mineral interface (Pedon 17, Fig. 3). In general, the gradual decrease in C content with depth toward the bottom tier of the organic horizons reflects increasing degree of organic matter decomposition with time (Howarth and Teal, 1979). In Pedon 19 of the Hell Hook marsh, the depth distribution of organic C was irregular reflecting the dominant fluvial environment adjacent to the streamside marsh (Fig. 3).

Organic Carbon Predictive Model

As sea-level continues to rise, forest lands that were beyond the effect of unusually high storm tides will become gradually inundated with brackish water, and eventually become transformed to tidal marshes when permanently submerged (Hussein and Rabenhorst, 2001). The time of permanent inundation marks the beginning of a new cycle of pedogenic development and is considered to be the time zero for the newly formed submerged upland tidal marsh soils (Hussein and Rabenhorst, 1999b). Because topography of the Chesapeake Bay area is generally characterized by low relief and gentle slopes, the elapsed time since submergence (age of the marsh) tends to increase with decreasing elevation of the submerged surfaces toward the open water as the organic

Table 1. Characterization data of organic soil (O), and underlying mineral soil (MS) for selected sites along Hell Hook (H) and Cedar Creek (C) marshes.[†]

Site	Depth	Soil	OC	OMD	D_b
	cm		g kg ⁻¹		Mg m ⁻³
H10	0–25	O	167	Fibric	0.22
	25–50	MS	15		1.30
H12	0–20	O	199	Fibric	0.23
	20–52	MS	21		1.07
H14	0–25	O	238	Fibric	0.10
	25–50	O	272	Hemic	0.13
	50–75	O	236	Hemic	0.17
H15	75–85	MS	58		0.53
	0–25	O	146	Fibric	0.13
	25–50	O	289	Hemic	0.07
	50–75	O	283	Hemic	0.08
	75–100	O	310	Hemic	0.08
	100–125	O	270	Hemic	0.07
	125–150	O	322	Hemic	0.09
	150–200	O	334	Hemic	0.10
	200–210	MS	16.3		0.80
	0–25	O	342	Fibric	0.10
H16	25–50	O	416	Hemic	0.08
	50–75	O	427	Hemic	0.08
	75–100	O	386	Hemic	0.07
	100–125	O	382	Hemic	0.07
	125–150	O	302	Hemic	0.10
	150–160	O	172	Hemic	0.23
	160–170	MS	6		1.42
	0–16	O	278	Fibric	0.18
C15	16–26	MS	64		0.69
	26–41	MS	27		1.23
C29	0–25	O	366	Fibric	0.09
	25–47	O	218	Hemic	0.18
C33 + 30‡	47–79	MS	7		1.35
	0–25	O	329	Fibric	0.11
C33 + 50	25–50	O	405	Hemic	0.09
	50–80	O	329	Hemic	0.12
	80–90	O	178	Hemic	0.33
	90–111	MS	33		0.61
C33 + 50	0–25	O	130	Fibric	0.19
	25–50	O	169	Hemic	0.15
	50–75	O	192	Hemic	0.14
	75–100	O	301	Hemic	0.11
	100–125	O	340	Hemic	0.08
	125–146	O	262	Hemic	0.15
	146–156	MS	13		0.93

[†] OC, organic C; OMD, degree of organic matter decomposition; D_b , bulk density.

[‡] 33 + 30 = Site 33 plus 30 m.

horizons thicken. To substantiate the hypothesis, thickness of the organic horizons was regressed against the elevation of the submerged geomorphic surfaces (relative to mean sea level) at Hell Hook ($Y = 0.342 - 0.967X$) and Cedar Creek ($Y = 0.389 - 1.096X$) sites. The inverse linear relationship was highly significant ($\alpha = 0.01$ with r^2 of 0.99) at both sites. Therefore, C sequestration (kg m⁻² over the entire thickness of the organic horizon) tends to increase with increasing marsh age as elevation of the submerged geomorphic surfaces decreases.

To develop a predictive model depicting C sequestration in coastal marshes, it was necessary to estimate rates of marsh vertical accretion and marsh age. The rate of marsh vertical accretion for the most recent period (approximately the last 150 yr) was determined using ²¹⁰Pb dating. The natural logarithm of the excess ²¹⁰Pb activity was regressed against depth, and the rate of vertical accretion was calculated by dividing the decay constant (0.031) by the slope of the regression line (Table 2). At Cedar Creek marsh, the rate of vertical accretion ranged

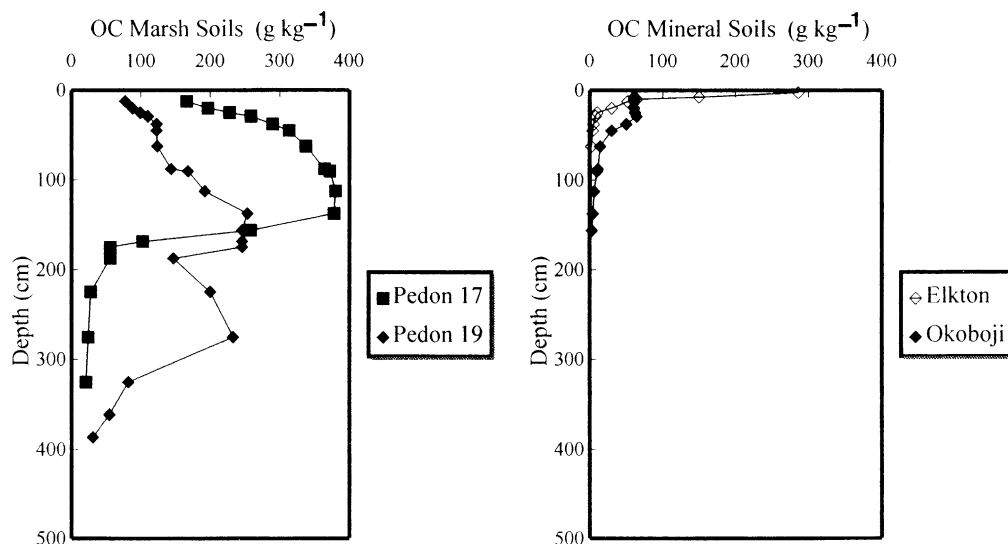


Fig. 3. The depth distribution of organic C (OC) in two coastal marsh soils (Histosols), Elkton soil (Ultisols) and Okobojo soil (Mollisols).

between 3.2 and 1.4 mm yr⁻¹ averaging 2.5 ± 0.9 mm yr⁻¹. At Hell Hook marsh, the rate of vertical accretion ranged from 1.5 to 3.2 mm yr⁻¹ averaging 2.2 ± 0.4 mm yr⁻¹. Because of the adopted sampling strategy, it is anticipated that rates of vertical accretion at both marshes covered the range in marsh ecology and habitats. Based on tidal records for the previous 40 yr, relative sea-level rise in the Chesapeake Bay ranged between 2.5 and 3.6 mm yr⁻¹ depending on the location (Hicks et al., 1983). Since 1900, rates of relative sea-level rise at Baltimore varied from 3.0 to 3.9 mm yr⁻¹ (Kearney and Stevenson, 1991). The reported rates of relative sea-level rise in the Chesapeake Bay area were variable due to differences in location, method of determination, and the length of time over which the history of relative sea-level rise was integrated. Given marsh variability, variability of the reported history of sea-level rise, and absence of field indicators suggesting marsh losses, the ²¹⁰Pb-average rates of marsh vertical accretion could be in good agreement with the reported range of relative sea-level rise in the Chesapeake Bay area. The *t* statistical test confirmed that the estimated average rates of marsh vertical accretion were significantly ($\alpha = 0.05$) within the reported range of relative sea-level rise. Therefore, and due to limited mineral-sediment input, both marshes are generally keeping pace with recent relative sea-level rise by organic C sequestration. The long-term rate of marsh vertical accretion before the

last century or two was determined using the ¹⁴C-based marsh age of the five basal peat samples collected from each marsh. The ¹⁴C age of the basal peat samples was regressed against the elevation of the submerged geomorphic surfaces to quantify the age-elevation relationship. The slope of the regression line was used to calculate the long-term rate of marsh vertical accretion (Table 2). The long-term rate of marsh vertical accretion before the last century or two at Hell Hook and Cedar Creek marshes was found to be 1.12 ± 0.2 ($r^2 = 0.94$) and 0.52 ± 0.1 mm yr⁻¹ ($r^2 = 0.97$), respectively. In marsh ecosystems, organic matter is generally altered with time due to decomposition and compression under its own weight causing consolidation of deeper organic layers with accompanying increases in bulk density (Kearney and Ward, 1986). Autocompaction of deeper organic layers shifts downward the original position of all the overlying sampling points within the organic horizon leading to erroneously low rates of marsh vertical accretion (Craft and Richardson, 1998). The basal peat samples selected for ¹⁴C dating were collected immediately above the dense, low *n*-value (high bearing capacity), submerged mineral soil surfaces. Therefore, the elevation of basal peat samples is stationary relative to sea-level datum and the estimated long-term rates of marsh vertical accretion are not considerably influenced by autocompaction. However, the long-term rates of vertical accretion are influenced by local physiographic char-

Table 2. ²¹⁰Pb counting rates as a function of depth, age elevation relationship and the corresponding accretion rates for selected cores at Hell Hook and Cedar Creek marshes.

Marsh	Technique	Model	r^2 †	Accretion rate mm yr ⁻¹
Hell Hook	²¹⁰ Pb	$\ln \text{Pb}^{210} = 1.887 - 0.098 (\text{depth cm})$	0.89	3.20
	²¹⁰ Pb	$\ln \text{Pb}^{210} = 2.735 - 0.205 (\text{depth cm})$	0.96	1.50
	²¹⁰ Pb	$\ln \text{Pb}^{210} = 1.832 - 0.165 (\text{depth cm})$	0.86	1.90
	¹⁴ C	Age = $234.4 - 895.0 (\text{elevation m})$	0.94	1.12
Cedar Creek	²¹⁰ Pb	$\ln \text{Pb}^{210} = 2.255 - 0.214 (\text{depth cm})$	0.77	1.40
	²¹⁰ Pb	$\ln \text{Pb}^{210} = 1.345 - 0.096 (\text{depth cm})$	0.71	3.20
	²¹⁰ Pb	$\ln \text{Pb}^{210} = 1.622 - 0.106 (\text{depth cm})$	0.84	2.90
	¹⁴ C	Age = $109.7 - 1927 (\text{elevation m})$	0.97	0.52

† Coefficient of determination.

acteristics of marsh ecosystems. For example, distance from the open water to the marsh ecosystem, tortuosity of tidal stream, and distance across the marsh from the tidal creek to the upland determine duration, and frequency of inundation as well as the time of permanent submergence (time zero for the newly formed submerged upland tidal marsh soils) at a given elevation point along the low-lying uplands (Hussein and Rabenhorst, 2001). An increase in the magnitude of these attributes tends to attenuate tidal energy through friction decreasing the frequency of inundation, and increasing the time needed to elapse to reach permanent submergence. The distance from the open water up to the tidal creek to the main inlet that feeds the Cedar Creek marsh (6.3 km) is considerably longer than that at Hell Hook site (2.1 km) and the creek is more tortuous. Also the distance across the Cedar Creek marsh from the tidal creek to the upland is approximately twice the corresponding distance at Hell Hook marsh (Fig. 1, 2). Thus, the frequency of inundation at a given elevation along the upland portion of Hell Hook site is higher than that at the corresponding elevation along the upland portion of Cedar Creek site. Accordingly, under a given scenario of sea-level rise low-lying uplands at Hell Hook site are submerging at a faster rate than that at Cedar Creek site. Therefore, it is anticipated that the ^{14}C -based long-term rate of marsh vertical accretion at Hell Hook site ($1.12 \pm 0.2 \text{ mm yr}^{-1}$) to be higher than that at Cedar Creek site ($0.52 \pm 0.1 \text{ mm yr}^{-1}$). For comparison, modern rates of relative sea-level rise showed acceleration over time. Kraft et al. (1987) have indicated that the present rate of relative sea-level rise along the U.S. Atlantic coast is as much as three to four times higher than the long-term trend over the last several thousand years.

The age of marsh pedons developed during the last 150 yr was determined using this equation.

$$\text{Age of marsh} = (E_0 - E_X)/\text{RVA}^{210}\text{Pb}$$

where E_0 is the elevation of the terrestrial/marsh edge, E_X is the elevation of the submerged geomorphic surface at sampling unit X, and $\text{RVA}^{210}\text{Pb}$ is the ^{210}Pb -based average marsh vertical accretion rate. Tidal dynamics, plant morphology, plant density, and their spatial distribution, as well as pedoturbation play an important role in sediment redistribution causing uneven accumulation of organic and inorganic sediments within marsh ecosystems. The undulating topography of marsh surfaces (Fig. 1, 2) may artificially increase or decrease thickness of the organic horizon at a given pedon creating a random error in marsh-age determination. Given the relatively narrow time frame of the ^{210}Pb dating technique (approximately 150 yr), the associated error may reach unacceptable limit. Therefore, for pedons developed during the last 150 yr, thickness of the organic horizon was measured relative to a stationary elevation (marsh/terrestrial edge) to eliminate the adverse effect of micro-scale topography on marsh age. For pedons developed before the last 150 yr, the age of the marsh was estimated using ^{14}C data. In this regard, the age of the marsh was determined using the derived age-elevation relationship

(Table 2) and the elevation of the submerged surface at a given point.

Because bulk density data (Table 1) showed no apparent increase with depth, it was assumed that subsidence within the organic horizons is of limited magnitude. Using age of pedons and rates of marsh vertical accretion, the estimated thickness of the organic horizons for the 26 pedons sampled at Hell Hook and Cedar Creek marshes was regressed against the observed values (Fig. 4). The linear relationship substantiated the validity of the assumption and indicated that 84% of the variability in thickness of the organic horizons within both marshes was explained by marsh age and rates of vertical accretion. For pedons developed during the last 150 yr, the estimated thickness of the organic horizons was comparable with the observed values at both marshes. For pedons developed before the last 150 yr, the deviation from the observed thickness of the organic horizons was generally $<10\%$ at Cedar Creek marsh. At Hell Hook marsh, the estimated thickness of the organic horizons developed before the last 150 yr was higher than the observed values by 16% on the average. While subsidence within organic horizons was generally of limited magnitude, it was slightly higher in older pedons at Hell Hook marsh than those at Cedar Creek marsh.

Marsh characterization data, and field observation have indicated that both marshes are keeping pace with sea-level rise by C sequestration. The inverse linear relationship between thickness of the organic horizons and elevation of the submerged geomorphic surfaces indicated that organic C sequestration (kg m^{-2} over the entire thickness of the organic horizon) tends to increase with marsh age as organic horizons thicken. Thickness of organic horizons was found to be a function of marsh age and rates of vertical accretion indicating limited subsidence within the organic horizons (Fig. 4). Because both marshes are keeping pace with sea-level rise and subsidence is limited, thickness of the organic horizons could be regarded as a reflection of sea-level rise with time. To normalize C sequestration against the effect

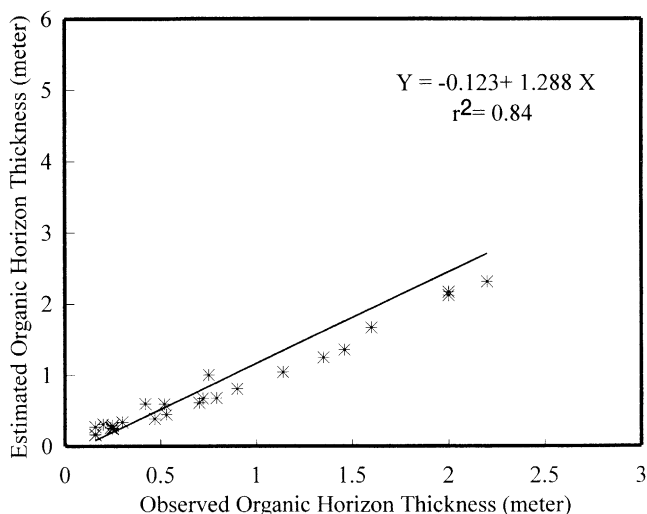


Fig. 4. The linear relationship between the predicted thickness of the overlying organic horizons and the observed values at Hell Hook and Cedar Creek marshes.

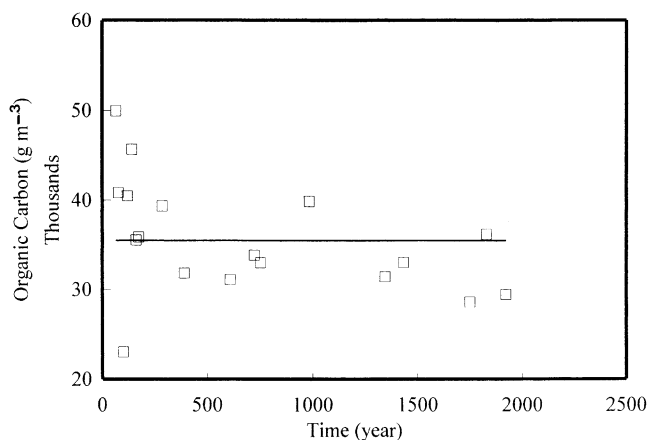


Fig. 5. The distribution pattern of the volumetric C content in the organic horizon of all pedons at Hell Hook and Cedar Creek marshes. The horizontal line represents the average volumetric C content (35.5 Kg m^{-3}).

of sea-level rise, the volumetric organic C sequestration (kg C m^{-3}) was calculated and the result was plotted versus time.

$$C_N = C_{TX}/T_x$$

where C_N is the normalized volumetric C content (kg C m^{-3}), C_{TX} is the organic C content (kg C m^{-2}) over the entire thickness of the organic horizon at sampling unit X, and T_x is thickness of the organic horizon (m) at sampling unit X. In the absence of the effect of sea-level rise, the volumetric organic C sequestration showed no specific pattern with time (Fig. 5). Therefore, Hell Hook and Cedar Creek marshes accrete vertically by C sequestration in the organic horizon and sea-level rise is the driving force.

Sequestration of organic C in forest soils is generally in the thin O and A horizons and decreases considerably with depth (Fig. 3). Thus, at the time of permanent submergence, the amount of organic C sequestered under forest conditions was initially incorporated in the newly formed submerged upland tidal marsh soils. Based on samples of the O and A horizons of higher-elevation forest soils, the initial organic C content incorporated in the newly formed submerged upland tidal marsh soils was estimated to be 8 kg m^{-2} . Analysis of C sequestration (g m^{-2}) in the upper 10 cm of the submerged mineral portion of marsh soils showed no specific pattern with marsh age (data are not shown). To incorporate soil variability within the model, the initial C content, and the mean C content (2.4 kg m^{-2}) within the upper 10 cm of the submerged mineral soils, were averaged. Therefore, the initial C content within the upper 10 cm of the submerged mineral portion of coastal marshes was considered to be 5.0 kg m^{-2} .

The predictive C sequestration model was developed using marsh age, rates of marsh vertical accretion, the mean volumetric C content, and the initial C content within the upper 10 cm of the submerged mineral portion. For pedons developed during the last 150 yr, the predicted organic C sequestration (kg m^{-2}) within a given thickness of the organic horizon was estimated using

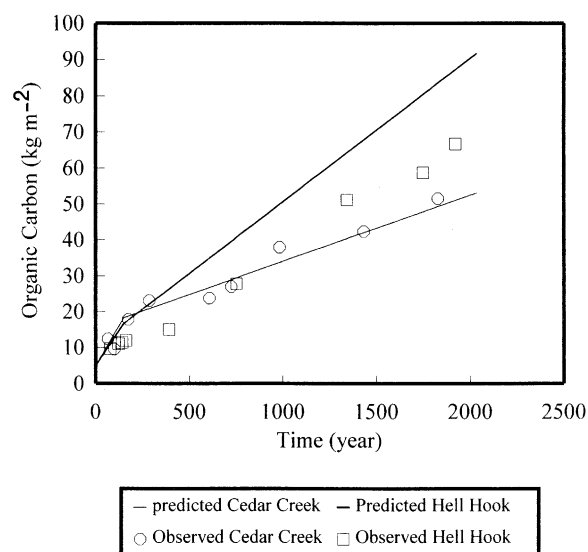


Fig. 6. The predictive C sequestration model at Hell Hook and Cedar Creek marshes.

Eq. [1]. Whereas, for pedons developed before the last 150 yr Eq. [2] was used.

$$\text{Prd. OCx} = (Gx \times \text{RVA}^{210\text{Pb}}) \text{ MVCC} \quad [1]$$

$$\text{Prd. OCx} = \{(150 \times \text{RVA}^{210\text{Pb}}) + [(Gx - 150)\text{RVA}^{14\text{C}}]\} \times \text{MVCC} \quad [2]$$

Prd. OCx is the predicted organic C sequestration at sampling unit X, Gx is the age of marsh at sampling unit X, $\text{RVA}^{210\text{Pb}}$ is the ^{210}Pb -based average marsh vertical accretion rate, $\text{RVA}^{14\text{C}}$ is the ^{14}C -based rate of marsh vertical accretion, and MVCC is the mean volumetric C content in the organic horizon (35.5 kg m^{-3}) (Fig. 5). As mentioned above, the organic C content of the underlying submerged mineral portion of marsh ecosystems was assumed to be 5.0 kg m^{-2} . The predicted organic C storage was considered to be the sum of C sequestrations in the organic horizon and in the underlying submerged mineral portion. The predictive organic C sequestration models were two-step linear functions (Fig. 6). Therefore, in these ecosystems C sequestration will continue to occur with increasing storage capacity as marsh age progresses. The model output and the observed values were in good agreement at Cedar Creek marsh (Fig. 6). Because subsidence within organic horizons of older pedons at Hell Hook marsh averaged 16%, some of the model output has deviated from the observed values (Fig. 6). During the last 150 yr, the predicted rates of C sequestration at Hell Hook and Cedar Creek marshes were 78 ± 14 and $89 \pm 32 \text{ g m}^{-2} \text{ yr}^{-1}$, respectively. For comparison and based on limited data, the average rate of C sequestration in nutrient-unenriched areas of the Everglades ($97 \pm 16 \text{ g m}^{-2} \text{ yr}^{-1}$) was similar to that of coastal marshes $83.5 \pm 23 \text{ g m}^{-2} \text{ yr}^{-1}$ (Craft and Richardson, 1998). Before the last few hundred years, the predicted long-term rates of C sequestration at Hell Hook and Cedar Creek marshes were 39.8 ± 7.1 and $18.5 \pm 3.6 \text{ g m}^{-2} \text{ yr}^{-1}$, respectively. Sampling protocol assured that C data is highly repre-

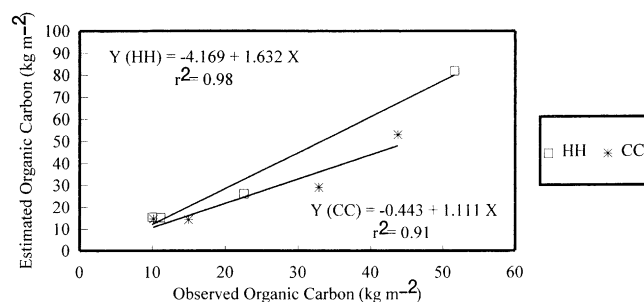


Fig. 7. Comparison of predicted vs. observed C values in pedons from the model validation sets at Hell Hook (HH) and Cedar Creek (CC) marshes.

sentative to marsh environment within a pedon. Sampling units were selected from two marshes that varied in physiographic characteristics and covered the range in various marsh ecology and habitats. Consequently, systematic spatial variability within marsh ecosystems (increasing sequestration of C in the organic horizons with decreasing elevation and increasing marsh age toward the open water), random spatial variability (marsh habitats; site characteristics; vegetation), and temporal variability are all integrated in the average volumetric organic C content. Therefore, the estimated rates of C sequestration are considered to be reasonably representative of coastal marsh ecosystems in the Chesapeake Bay, Maryland. The sampling protocol adopted in this study placed 10% accuracy (allowable percentage deviation from the estimated mean value) and 80% confidence on the predictive models and the estimated rates of C sequestration in coastal marsh ecosystems (Hussein and Rabenhorst, 1999a). To validate the C predictive models, an additional four pedons from each marsh that were not included in the model development were utilized. The age of these pedons was also estimated using ^{210}Pb and ^{14}C dating. Organic C data from these pedons were in good agreement with the predicted values at Hell Hook and Cedar Creek marshes with coefficient of determination equal to 0.98 and 0.91, respectively (Fig. 7).

Carbon Sequestration in Forest and Agricultural Soils versus Coastal Marshes

Differences in the depth distribution of organic C in soils developed under forest and prairie vegetation is in the mode of C deposition (Kononova, 1966). Under forest vegetation, organic C addition occurs at the soil surface where leaf litter and woody material accumulate. The deep thick poorly integrated tree's root-system lacks fine roots, and is generally regarded as a below ground long-term C storage (Slobodian et al., 2002). Therefore, C sequestration in Elkton soils (forest soil) is generally in the O and A horizons, and decreases sharply with depth (Fig. 3). Accordingly, the storage capacity of upland forest soils as a C sink is generally limited to the thin O and A horizons (approximately top 10-cm). The depth distribution of organic C in Okoboji soils (fine, smectitic, mesic Cumulic Vertic Endoaquolls) showed gradual decrease with depth (Fig. 3). This trend reflects the influence of the integrated effect of the previous

vegetative cover (prairie grasses), land use change, physiographic position, soil environment, and time. Okoboji soils are poorly drained soils that developed in closed depressions on till plains and moraines (Soil Survey Staff, 1998b). Therefore, these soils receive soluble and insoluble organic C particulates from upslopes to form a thick A horizon (Honeycutt et al., 1999a, 1999b). The abundant deep dense fine root system of prairie grasses contributed (upon decay) organic matter to a greater depth to form over thickened A horizon. Extensive cultivation of grassland soils has enhanced soil aeration and the sequential decomposition of organic matter, as well as the transport of soil C from up-slopes to depressional soils (Beare et al., 1994; Pennock and Van Kessel, 1997). Therefore, the C-storage capacity of Okoboji soils (Molisol) is generally greater than that of Elkton soils (Ultisol) developed under forest vegetative cover (Fig. 3). The depth distribution of organic C in Okoboji soil extends below 1 m (Fig. 3). However, soil color of the B horizon as well as abundance of redoximorphic features suggested that organic C is localized in micromorphological features rather than uniformly distributed within the soil matrix (Soil Survey Staff, 1998b). Given the high bulk density of mineral soils, including the B horizon in the calculation of C stocks tends to overestimate C sequestration in Okoboji soils. Thus, to estimate the rate of accumulation, the amount of organic C sequestered in the Ap horizon (80 cm thick) of Okoboji soil (g m^{-2}) was divided by the age of the soil (3000 yr; Walker, 1966). The rate of C sequestration in the Ap horizon of Okoboji soils was $12.9 \text{ g m}^{-2} \text{ yr}^{-1}$. This result was in agreement with reported data where the annual C storage rates for forest, tundra, desert, and grassland ecosystems ranged from 0.2 to $12.0 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Schlesinger, 1990). The rate of organic C sequestration in Okoboji soils was less than half the long-term rate of C sequestration in coastal marsh ecosystems. Generally, soil-forming processes are operating at slow rates, and considerable time is needed to achieve steady-state condition. However, given the age of Okoboji soils, it is anticipated that organic C content in the Ap horizon is at a dynamic equilibrium with soil environment (Yaalon, 1983).

There is a general agreement that decreasing the intensity of tillage and enhancing the complexity of crop rotation increase C sequestration capacity in mineral soils of agroecosystems. However, reported data assessing the potential for C sequestration in agricultural soils were variable. Optimizing agricultural practices have increased C sequestration rate to a level ranging from 24 to $40 \text{ g m}^{-2} \text{ yr}^{-1}$ (Lal et al., 1999) whereas previous estimates ranged between 10 and $50 \text{ g m}^{-2} \text{ yr}^{-1}$ (Lal et al., 1998). In Canada, rate of C sequestration ranged from 50 to $75 \text{ g m}^{-2} \text{ yr}^{-1}$ (Dumanski et al., 1998). Global database, revealed that in response to adopting best management practices, C sequestration rates in agricultural soils averaged $57 \pm 14 \text{ g m}^{-2} \text{ yr}^{-1}$ reaching a new steady-state condition within 15 to 20 yr (West and Post, 2002). The lack of consistency in the reported rates of potential C sequestration in agriculture soils could be attributed to many factors including but not limited to

duration of the field study, depth to which soil organic C was estimated, variability in annual weather conditions, crop rotation system, soil type, erosion, and intensity of cultivation in the initial management regime.

For comparison, C sequestration in mineral soils of agro and upland forest ecosystems is generally of limited capacity and tends to reach steady-state condition within relatively short time. In coastal marsh soils, C sequestration will continue to occur with time by accumulation in the organic horizons, and with increasing storage capacity (Fig. 6). In agricultural mineral-soils, C stocks are generally derived from biomass production that requires petroleum-derived energy to manufacture and transport inputs necessary for crop management. In contrast, C sequestration in coastal marsh ecosystems is mainly supported by sea-level rise.

Future Carbon Sequestration in Coastal Marsh Ecosystems

Although there is a general scientific consensus that a significant sea-level rise is immanent, the magnitude and the timing of sea-level rise are still uncertain. Hoffman and Titus (1983) identified the primary factors that might influence future rates of sea-level rise. Linking the major factors has led to four scenarios of projected worldwide sea-level rise ranging from conservative (low) to high. The most restrictive and moderate assumptions were integrated to generate the conservative and mid-range low scenarios for the next 100 yr. Because these two scenarios were less dramatic in magnitude, they were selected to predict future C sequestration in two upland forest soils upon their transformation to coastal marshes. These soils are very near to but slightly above mean high water (MHW) (8 cm above MHW at Cedar Creek and 12 cm above MHW at Hell Hook). In general, most soil forming processes are so slow that their impact on soil development is only evident over longer time frames than Hoffman's 100-yr projections. Therefore, assuming that these rates of sea-level rise for both scenarios remain constant, Hoffman's predictions were ex-

tended from 2100 to 2300 AD. The future C sequestration model was assessed based on the assumptions that both marshes are keeping pace with future rates of relative sea-level rise, and development does not prevent or restrict the lateral migration of coastal marshes. The future C sequestration occurs primarily by accumulation in the organic horizons and is mainly supported by sea-level rise (Fig. 8). Future C sequestration during the first 100 yr ranged from 250 to 570 g m⁻² yr⁻¹, averaging 400 ± 162 g m⁻² yr⁻¹. Modeling C sequestration indicated that coastal marsh ecosystems tend to sequester C continuously with increasing storage capacity as marsh age progresses. Thus, C sequestration in coastal marsh ecosystems under positive accretionary balance acts as a negative feedback mechanism to global warming.

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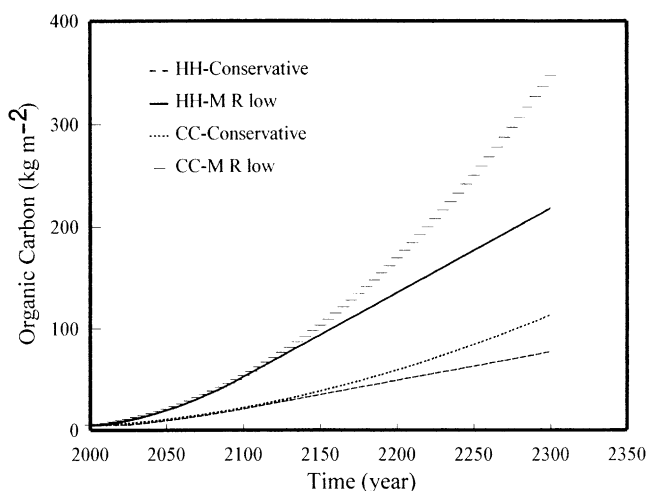


Fig. 8. Predicted C sequestration in Hell Hook (HH) and Cedar Creek (CC) marshes, based on models using the conservative and mid-range (MR) low sea-level rise scenarios of Hoffman and Titus (1983).

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